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The measured performance of Plumbicon camera tubes November 1963

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THE BRITISH BROADCASTING CORPORATION
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RESEARCH DEPARTMENT

THE MEASURED PERFORMANCE OF PLUMBICON CAMERA TUBES NOVEMBER 1963

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SUMMARY

The performance of ten sample Plumbicon television camera tubes has been measured and the results are discussed. To determine the practical importance of known defects of the tube in its present form, further operational trials are desirable.

1. INTRODUCTION

The Plumbicon camera has been under development by the Philips organisation in Eindhoven for at least eight years. About three years ago, a successful camera was demonstrated, but at that time, no tubes were available to other organisations. The early experimental Plumbicon tubes were found to have a very short life, but more recently, they have been improved substantially, and it is understood that production Plumbicons will have a guaranteed life of 500 hours.

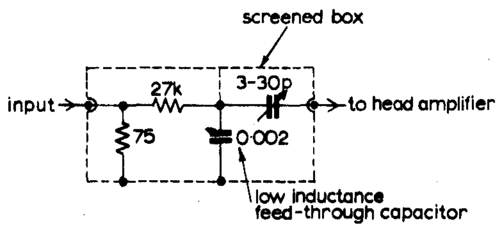
It has been known for some time that the Plumbicon camera tubes currently available have a pronounced deficiency in response to light of wavelengths longer than 630 nm, but in the Research Laboratories of Philips, a variant of the original design has recently been found to have a response extending beyond 700 nm. This new red-sensitive tube is not yet in production; it is, however, thought that it will eventually supercede the original lead-oxide Plumbicon.

2. PHYSICAL DETAILS

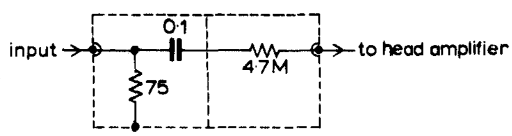
The Plumbicon is a low-velocity camera tube, 207·5 mm overall length and about 30 mm in diameter. The target material is photoconductive lead-oxide and the image dimensions are 12 mm by 16 mm (the diagonal is 20 mm). Deflection is carried out magnetically. The tube is intended to be focused by a combination of pre-set magnetic and variable electrostatic fields in order that rotation of the image is avoided when making adjustments. The capacity of the target to the rest of the tube is about 5 pF, and this is increased by an additional 5 pF when the tube is inserted in the deflecting/focusing assembly. This total capacitance represents the output impedance of the tube. The highlight signal-current is in the range 0·1 to 0·6 μA and the optimum average signal-current is approximately 0·15 μA. It is claimed that the dark-current of the tube is exceedingly small.

3. MEASUREMENTS

The Plumbicon tubes were measured whilst operating in a Philips black-and-white television camera constructed and supplied on loan by Peto-Scott Ltd. of Weybridge, Surrey. Adjustment of the equalization for the input time-constant of the head amplifier was made by means of a 'dummy tube' input probe constructed for the purpose. The circuit diagram of this device is shown in Fig. 1(a) and the component values were adjusted after careful measurement of a Plumbicon tube connected to the head amplifier under operating conditions. Measurements indicated that the capacitance of a typical Plumbicon tube in situ was 10·27 pF and the 'dummy tube' was adjusted to have this capacitance.



(a) Variable capacitance adjusted to simulate capacitance of Plumbicon tube when in scanning yoke (i.e. 10·27 p)



(b)

Fig. 1 - Plumbicon dummy tube

(a) High-frequency probe 50 kc/s - 10 Mc/s
(b) Low-frequency probe 100 c/s - 50 kc/s

The high-frequency probe illustrated in Fig. 1(a) fails to simulate the Plumbicon camera tube at frequencies below 30 kc/s since the impedance of the shunt capacitance (0·002 μF) then becomes significant compared with the source impedance. The probe shown in Fig. 1(b) is used for low frequencies only and represents a constant current source by virtue of the 4·5M resistor. No attempt is made to obtain the correct output capacitance in this probe. The exchange of probes should take place when the test signal is about 50 kc/s.

The tubes were measured for:

Resolution
Colour Response
Sensitivity
Signal-to-Noise Ratio
Failure to Erase (Lag)
'Sticking'
Gamma

3.1. Resolution

In making measurements of the resolution of a camera tube, it is, of course, necessary to take into account the performance of the head amplifier and the camera control unit. The head amplifier response was made uniform from 0 to 7 Mc/s, but it was found that the response of the camera control unit varied with time and temperature so an alternative unit was made from a standard BBC blanking amplifier, together

with an amplifier having a gain of 15 dB. The measurements given in this report were obtained by this method. All resolution measurements were made with light of approximately equi-energy spectral distribution although it has since been found that there is a small variation in the resolution of the Plumbicon tube to light of different wavelengths. Separate experiments indicate that the response to 5·5 Mc/s bars (625-line Standard I) illuminated by light having a colour temperature of approximately 3,000°K and an energy distribution due to an incandescent tungsten source would be approximately 5% less than that measured with equi-energy light. Experiments performed by E.M.I. Ltd.* have shown that response to 5·5 Mc/s bars in blue light exceeds that with orange light, as determined by Ilford spectrum filters, by approximately 7%. This is due to the ready absorption of the blue light near to the front surface of the target layer, whereas orange and red light are not so readily absorbed by the lead-oxide material and light of this colour becomes diffused before it is eventually absorbed.

Alignment of the tube was carried out using test cards; the resolution was then measured by means of high-contrast square-wave grating patterns which were introduced into a small area of a standard scene. The scene (a general view of a cricket match) was used to ensure normal operation of the camera in all respects while the resolution was being measured at one point in the field. The tube was first focused to give maximum response on a 5·5 Mc/s resolution pattern placed in the centre of the field and this was then changed to one representing a 550 kc/s signal. The response to this coarse pattern was regarded as 100% and the response at all other frequencies was then expressed as a percentage. The results quoted are without aperture correction and refer to the centre of the field.

Variation of resolution in various parts of the field of a television camera must always be, to a large extent, a function of the excellence of the scanning yoke since orthogonal landing of the beam should be maintained over the whole of the scanned area. The resolution at the outer limit of Zone Two† was measured:

(a) When the scanning beam was focused for maximum resolution in the centre of the field.

(b) When the scanning beam was focused for maximum resolution at the position of the test pattern.

The results indicate that the design of the scanning yoke in the Plumbicon camera is not optimum. There is also reason to believe that a significant improvement in the performance of the tube (independently of improvements in the performance of the yoke) could be obtained by separation of the field-mesh and the wall-anode electrodes. Experience with the Vidicon camera,[1] which is physically very similar, indicates that improved landing conditions of the beam would be obtained. Furthermore, the overall resolution of the tube (particularly where there is any tendency to surplus scanning-beam current) would be substantially improved by elimination of the trapped ions which linger in the region of weak field near the target.

The potential of the target for each individual tube was adjusted to the point at which there is a distinct 'knee' in the curve of output signal current versus target potential; this indicates that a point of saturation has been reached.

* Information received verbally from Dr. H.G. Lubszynski (E.M.I. Research Laboratories).

† Zone Two is defined in Drawing P. and I.D. 7209.7.3A. Its outer boundaries include parts of a circle of diameter equal to the length of the active scanning line and centred in the active picture area.

Peak signal current was 0·3 μA at the highlight brightness used. The target potential determined by this method varies slightly from tube to tube but lies in the region 35 V to 45 V. In every case, the beam current was so adjusted that peak highlights in the scene were sufficiently discharged.

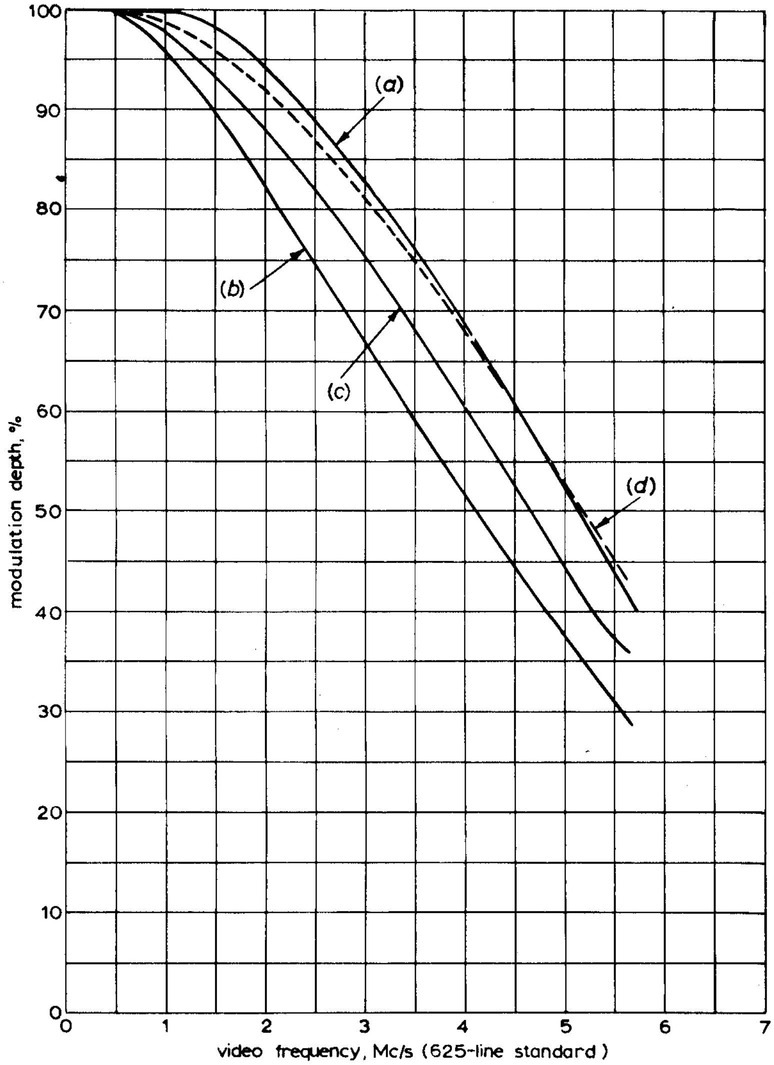


Fig. 2 - Resolution of Plumbicon camera tube for 0·3 μA peak signal current

(a) Upper limit of 10 standard Plumbicons
(b) Lower limit of 10 standard Plumbicons
(c) Mean of 10 standard Plumbicons
(d) Red-sensitive Plumbicon

Some tubes, not amongst those which have been loaned to the BBC, have been reported to exhibit a serious defect, similar in appearance to the 'peel-off' effect originally exhibited by C.P.S. Emitron tubes. This has an important repercussion on the resolution of the tube and attention is drawn to Section 3.7. in which the defect is discussed.

Ten Plumbicon tubes were measured and the graph of Fig. 2 shows the upper and lower limits of this sample, together with the mean result. The consistency of

the ten tubes appears to be good, but the resolution of the Plumbicon is undoubtedly inferior to the 4½ in image orthicon which will normally give about 75% modulation at 5 Mc/s (625-line standard).

One red-sensitive tube has been examined. When first measured it had a resolution substantially better (60% modulation at 5 Mc/s) than that of any of the normal Plumbicons, but after several days' use in a colour camera, the tube was returned for further measurements and was found to have deteriorated somewhat although it was still comparable with the best of the standard tubes (see Fig. 2). The reason for the loss of resolution is not known for certain but it is thought that it might be due to 'gassing' within the tube. A second red-sensitive tube supplied on loan by Philips Research Department proved from the outset to be so soft that it has not been possible to make any measurements.

Other tests concerning the resolution of the normal Plumbicon tube included an investigation into the effect of increased signal current. Two tubes were measured with the highlight signal current adjusted, in turn, to 0·15 μA, 0·3 μA and 0·6 μA, and the results are shown in Fig. 3. In each case, the beam current was just sufficient to discharge highlights fully. Philips' recommendation that the mean signal current should be 0·15 μA is not incompatible with a peak signal current of 0·3 μA. 0·6 μA peak signal current must be regarded as excessive.

Corner resolution was measured at a point on the outer boundary of Zone Two, and the results are shown in Table 1 below.

TABLE 1

Corner Resolution of Two Plumbicon Tubes at 5·5 Mc/s

TUBE NO.	POINT OF MEASUREMENT	CORNER RESOLUTION % - FOCUSED FOR OPTIMUM AT CENTRE	CORNER RESOLUTION % - FOCUSED FOR OPTIMUM AT CORNER	CENTRE RESOLUTION % - FOCUSED FOR OPTIMUM AT CENTRE
3978	Top Left	7	31	34
	Bottom Left	23	32	
	Top Right	14	32	
	Bottom Right	18	32	
3401	Top Left	5	28	32
	Bottom Left	22	30	
	Top Right	20	30	
	Bottom Right	7	30	

It will be seen that refocusing the beam regains corner resolution until it is nearly equal to the centre resolution. This would indicate that the scanning yoke of the Peto-Scott camera leaves much to be desired.

3.2. Colour Response

Colour response was measured with the aid of an apparatus constructed specially for this purpose. A small area of selected colour is produced by means of

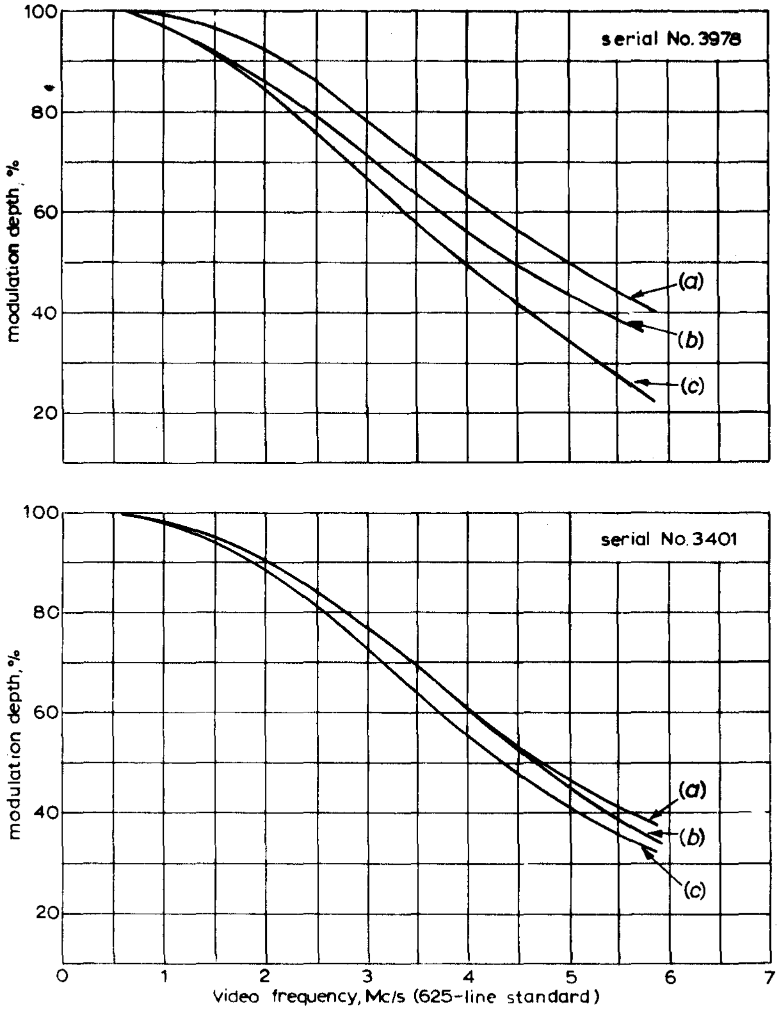


Fig. 3 - Variation of resolution with peak signal current for two standard Plumbicon tubes

Serial No. 3978

(a) 0·15 μA)
(b) 0·30 μA) Peak signal current
(c) 0·60 μA)

Serial No. 3401

(a) 0·15 μA)
(b) 0·30 μA) Peak signal current
(c) 0·60 μA)

a very narrow-band metal-dielectric filter which is rear-illuminated and displayed to the camera. The points of 50% maximum transmission in these filters are approximately 20 nm apart. Adjacent to the colour area is another small area of uniform but adjustable luminance produced by two overlapping neutral density wedges also rear-

illuminated and arranged that they may be moved mechanically in opposition. The density of the neutral area is calibrated against wedge position and a camera tube viewing the two areas side by side, one coloured and one neutral, is thus simply used as a null indicator to produce output signal pulses of equal amplitude from either

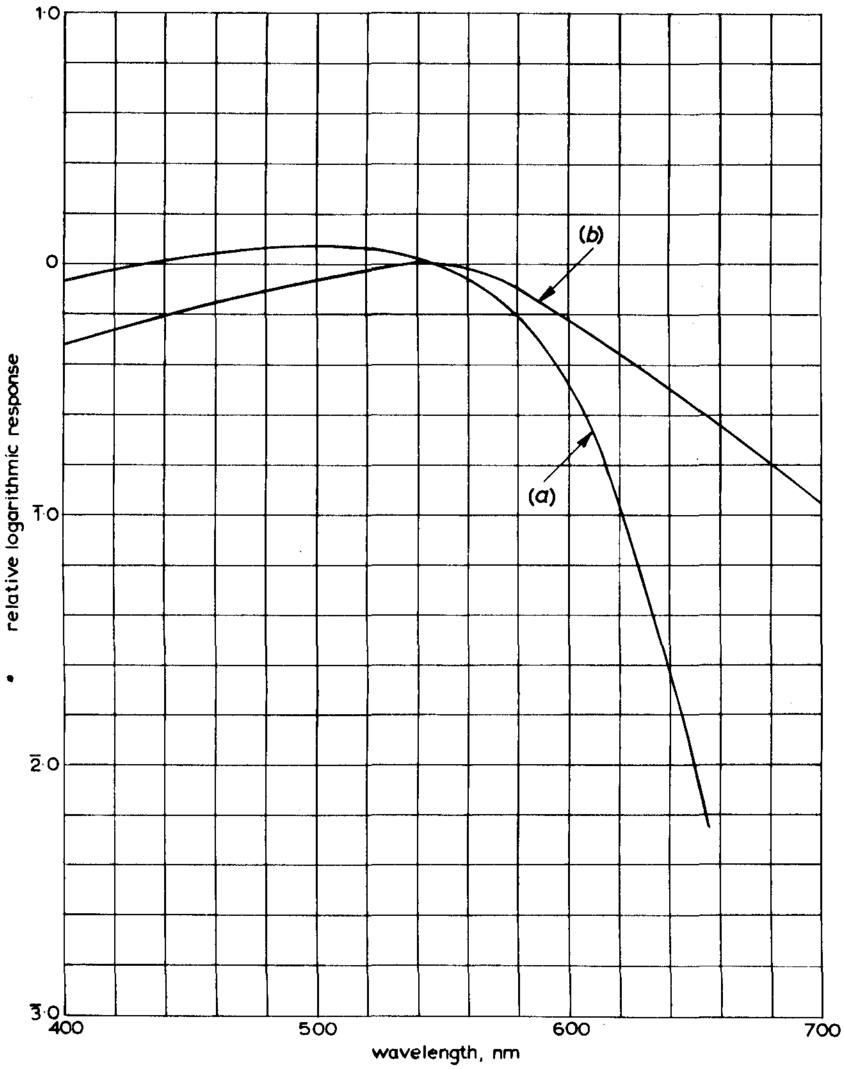


Fig. 4 - Equi-energy colour response of Plumbicon tubes (no gamma correction)

(a) Mean of 5 standard Plumbicons
(b) Red-sensitive Plumbicon

area. A correction is made to the results for the effect of the skirts of the pass-band characteristic of each of the colour filters. The response of the camera tube has been plotted in terms of equi-energy illumination, approximating to daylight conditions, and also tungsten studio illumination of colour temperature 3,000°K (333 mireds).

It will be seen from Fig. 4 that the ordinary Plumbicon camera tube has a substantially satisfactory response to wavelengths between 400 and 600 nm. There-

after, however, the response decreases very rapidly and is only 1% at 650 nm. The response to tungsten illumination is shown in Fig. 5. These results are typical of all the normal Plumbicons measured and they appear to have been quite consistent in this respect. It is felt that the lack of red sensitivity is such that the tube may give rise to considerable difficulty with skin tones and make-up when used in a

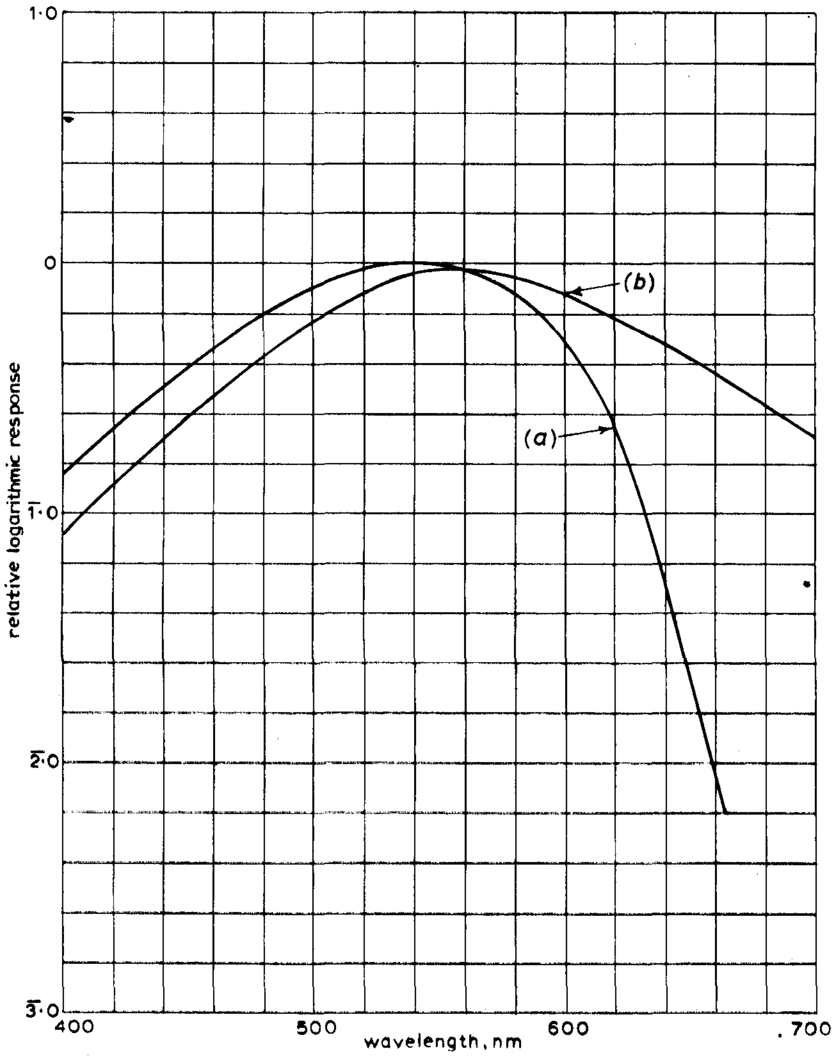


Fig. 5 - Colour response of Plumbicon tubes to illumination at a colour temperature of 3000°K (no gamma correction)

(a) Mean of 5 standard Plumbicons
(b) Red-sensitive Plumbicon

monochrome camera and, unfortunately, the response is such that there is little hope of using any comprehensive colour-correction filters since the sensitivity would be drastically curtailed before anything approaching the optimum colour response of a monochrome camera[2] could be obtained. The one red-sensitive Plumbicon camera tube so far examined shows that adequate colour response can be obtained in this type of tube.

The additional red-sensitivity of the experimental tube is obtained without alteration of the response to wavelengths shorter than 600 nm and although we are at present requested by the Philips organization not to regard the performance of this one red-sensitive Plumbicon tube as indicative of what may become available in production, it is reassuring that in at least one sample, a satisfactory colour response has been achieved.

3.3. Sensitivity

The sensitivity of the Plumbicon tube is of particular interest and is best expressed in terms of the highlight brightness required in the scene to give a satisfactory signal-to-noise ratio while maintaining a depth of field equal to that given by other television cameras. It is necessary to remember that the spectrum of the noise produced by this camera is fundamentally triangular, but is further modified by aperture correction. In the case of the image orthicon, the noise energy is substantially uniform at all frequencies and that tube requires less aperture correction. It is well known that the visibility of triangular noise is less, for a given r.m.s. value, than that of uniform-spectrum noise and it is usual to allow a weighting factor of, say, 6 dB in favour of the triangular spectrum for monochrome applications. Thus, a measured signal-to-noise ratio of 32 dB in a Plumbicon channel is approximately equivalent, in annoyance value, to a 38 dB signal-to-noise ratio for an image orthicon channel. The image diagonal of the Plumbicon camera is 20 mm against 40 mm in the image orthicon camera and depth of field, which is a function of the absolute diameter of the exit pupil of the lens, is therefore equal in the two cameras when the Plumbicon is operated with an aperture two stops larger than the image orthicon. The acceptance level stated in the P.822 4½ in image orthicon specification calls for a maximum photocathode illumination (0·125 lumens per square foot) which is equivalent to a scene highlight brightness of 25 ft-L with lens aperture f/5·6. To give equal target illumination in the Plumbicon, with equal depth-of-field, the scene highlight brightness required is therefore only one quarter of this value (i.e., 6·25 ft-L at f/2·8). It is, of course, likely to prove more difficult to obtain high resolution in lenses (particularly zoom lenses) of very large aperture.

The operating conditions of the Plumbicon are, however, variable to suit a range of target illuminations (unlike the image orthicon which has a fixed operating point referred to as the 'knee' of the light transfer characteristic) and the Plumbicon sensitivity is not simply four times that of the image orthicon. Depending on the signal current used, and hence the signal-to-noise ratio, the absolute illumination required by the Plumbicon target may be more, or less, than that of the image orthicon photocathode. Measurements were made at three different highlight signal currents (0·15 μA, 0·3 μA, and 0·6 μA) which correspond to signal-to-noise ratios of 32 dB, 38 dB and 44 dB respectively at the output of the head amplifier of the Peto-Scott camera. Thus, in a comparison between the image orthicon and the Plumbicon for monochrome applications, the sensitivity of the latter may be measured with, say, 34 dB signal-to-noise ratio to give pictures with noise visibility approximately equal to those of the average P.822 4½ in image orthicon. This includes a small allowance for the extra equalization and extra gamma correction required by the Plumbicon.

Maximum and minimum sensitivities given by the ten normal-type Plumbicon tubes measured are shown in Fig. 6. The typical and minimum acceptance sensitivities

of the P.822 4½ in image orthicon are 17·5 ft-L and 25 ft-L, respectively. The mean value of target illumination required by the Plumbicon was 0·13 lumens per square foot for 34 dB signal-to-noise ratio which corresponds to a highlight brightness on the scene of about 8 ft-L. This indicates that the Plumbicon tube is about twice as sensitive and has a somewhat more desirable noise distribution (for monochrome applications) than the typical image orthicon under conditions of equal depth of field.

For colour television applications, it is, however, preferable to make the comparison on the basis of a peak signal current of 0·3 μA (38 dB signal-to-noise

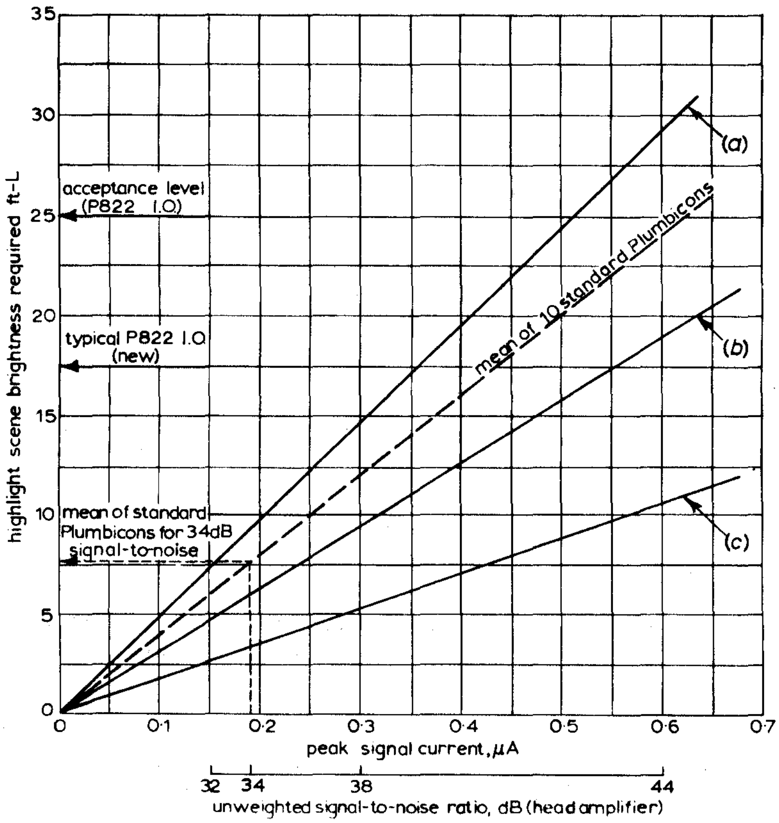


Fig. 6 - Sensitivity of standard Plumbicon camera tubes

(a) Upper limit of 10 standard Plumbicons
(b) Lower limit of 10 standard Plumbicons
(c) Red-sensitive Plumbicon

ratio) which would allow for the fact that in colour television applications, the concentration of noise energy in extreme high frequencies is undesirable because of cross-colour effects.

The sensitivity measurements were made with a light source of approximately equi-energy distribution and measurements to tungsten illumination give about 10% lower sensitivity. The red-sensitive tube, however, was approximately twice as sensitive to equi-energy light as the best of the normal Plumbicon tubes.

The signal-to-noise ratio of the Plumbicon tube is determined almost entirely by the design of the head amplifier. In the Peto-Scott channel, the signal-to-noise ratio was 38 dB when the signal current was 0·3 μA. It seems possible that a head amplifier of more elaborate design could show a significant improvement upon this performance. The signal-to-noise ratios refer to the black-to-white signal excursion divided by r.m.s. noise voltage, unweighted and without gamma correction, which is always removed before making measurements of signal-to-noise ratios.

3.4. Lag

The total lag exhibited by the Plumbicon tube is the result of two contributions. The first is photoconductive lag, which is also encountered in the Vidicon camera tube, and may be described as the continued growth of the stored image after the light stimulus has been removed. It is due to the delayed release of trapped charge-carriers in the photoconductive material. The other component of the lag is due to imperfect erasure of the stored charge pattern by the scanning beam; this is usually called capacitive lag. In the standard Plumbicon tube, the photo-conductive lag is small and imperfect erasure predominates.

The lag was measured by means of a small area of light pulsed-on for 20 ms and exposed to the camera once in every 10 fields. The exposure was timed to begin immediately after the scanning spot had passed the area of the target upon which the light was focused. Thereafter, the tube was scanned normally for 10 fields but during this time no further exposure of any sort was made. The output from each of the ten scans following exposure was measured and plotted. The results are given in Fig. 7.

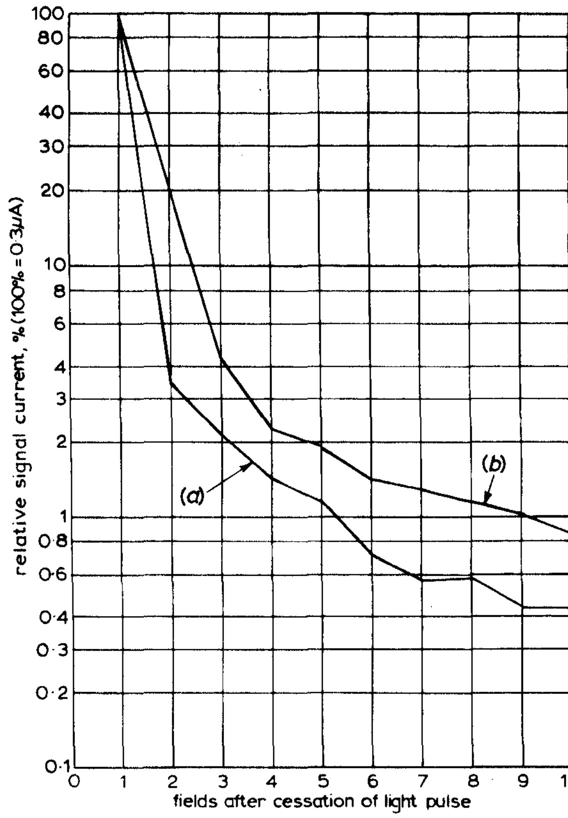


Fig. 7 - Lag in the Plumbicon

(a) Standard Plumbicon
(b) Red-sensitive Plumbicon

It will be seen that after two scans, the output of a normal Plumbicon tube has dropped to approximately 3% of that obtained from the first scan following exposure. Thereafter, successive scans produced 2%, 1½% and 1%. This is comparable with the lag of a typical P.822 4½ in image orthicon which, of course, is regarded as very satisfactory from this point of view. The lag of the single red-sensitive tube examined is significantly greater than that of the normal Plumbicon, worse than that of the P.822 4½ in image orthicon, and similar to that of the C.P.S. Emitron. The difference between this and the standard Plumbicon tube is thought to be due to an

increase in the photoconductive component of the lag since capacitive lag should not be significantly different in the two versions of the tube. The introduction of impurities to increase the red-response of the tube may well have increased the number of 'traps' capable of holding charge-carriers. There is a tendency for a long 'tail' of about 1% white signal to exist for several scans after extinction of the light and this is sufficient to give rise to noticeable 'trailing' effects on movement. The effect may prove to be an embarrassment in some applications. It is again emphasised, however, that the red-sensitive tube result was obtained from a single example and the manufacturers state that there is no guarantee whatsoever that this result would be repeated.

It may, however, be mentioned in passing that one or two of the normal Plumbicon tubes given to other organizations have exhibited very severe lag, certainly comparable with that of the Vidicon camera. These were second-grade, so-called 'setting-up' tubes, but the examples serve to indicate that present production difficulties do include the incidence of tubes with severe lag.

3.5. 'Sticking'

All the tubes were examined for a tendency to 'sticking' by exposure to a high-contrast pattern for 30 seconds. The camera was then exposed to a plain white field and the time taken from remnants of the pattern to disappear was measured in seconds. Most tubes satisfactorily passed the image orthicon specification which requires that, under these conditions, the image shall have disappeared within 10 seconds. A number of tubes examined showed no measurable tendency to stick at all. It was found that a tendency for a new Plumbicon to stick could often be cured by increasing the target potential by 30% to 40% for a period of 15 minutes, thereafter returning to normal operating conditions. It is not known whether prolonged service gives rise to any tendency to stick permanently as in the case of image orthicons, but there are indications that tubes with an inherent tendency to stick may sometimes occur in production.

3.6. Gamma

The light transfer characteristic of a number of tubes has been measured and the result is shown in Fig. 8. The slope of the average characteristics of the tubes is not significantly different from unity and the spread of points above and below this line is more likely to be due to experimental error than to any other cause. It should be remarked that the spread indicated in Fig. 8 not only includes spread of the ten tubes measured with an equi-energy light source but also the results for the light transfer characteristic of each tube measured to red, green and blue light sources separately.

3.7. The 'Peel-Off' Effect

Finally the 'peel-off' effect must be mentioned. None of the ten standard Plumbicons nor the red-sensitive tube loaned to the BBC have shown this effect, but some visitors from Germany recently stated that they had examined tubes and found this to be a very serious defect. Subsequently, discussion with E.M.I. showed that they, too, had received Plumbicon tubes from Philips which exhibited this defect and one such tube was loaned to us for examination.

The effect is very similar in appearance to that of the 'peel-off' encountered in the C.P.S. Emitron, in that one area of the target (in our case, the bottom right-hand corner) slowly acquired a charge which took the signal to peak white and crushed off all picture information within that area. This occurred when there was insufficient beam current to discharge the target following exposure to light in that part of the image. The effect is probably a function of the beam landing condition and a tube with poor electron gun alignment would seem to be more likely to be affected since the beam will discharge the target less efficiently in some areas than it does in others. When the light incident upon the target is limited, the effect does not occur and therefore it is also a function of the signal current. It is sometimes

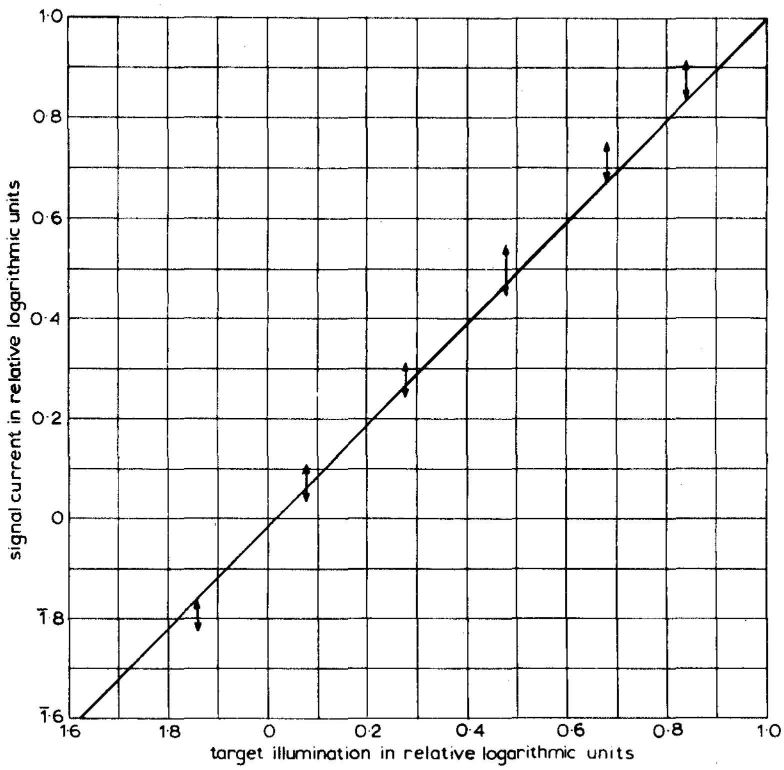


Fig. 8 - Light transfer characteristic of Plumbicon

N.B. arrows indicate total spread of 10 standard Plumbicon tubes, each one measured for red, green, blue and white light

possible to prevent such an area of 'peel-off' from showing in the output picture by the use of increased beam current but since this means that in other parts of the picture the beam current is unnecessarily large, the resolution is degraded considerably. In the tube loaned to us by E.M.I. Ltd., for example, centre resolution was 35% at 5·5 Mc/s with the beam current adjusted to suit all but the small area of 'peel-off' in the bottom right-hand corner. When, however, the beam current was increased until this area of 'peel-off' was no longer visible, the resolution in the centre of the picture had dropped to 12½% modulation at 5·5 Mc/s. Dr. Lubszynski (E.M.I.) is confident that the use of a separate field mesh, in a manner similar to

that which he has successfully used in the Vidicon camera, would permit the use of higher beam currents without loss of resolution and would also improve landing conditions in the corners of the target area so that the 'peel-off' effect could be avoided.

4. CONCLUSIONS

It would seem that some Plumbicons exhibit defects which have not been apparent in those loaned to the BBC, and the experience of others have been less satisfactory. It is therefore important that more experience of production Plumbicons should be gained, particularly to determine whether the BBC's experience so far has been restricted to tubes selected for absence of these defects. The colour response of the normal Plumbicon is such that it would need extensive field trials (in a better camera than that so far provided) before it could be regarded as acceptable for use in ordinary black-and-white studio applications. For use in the colour camera where the light energy supplied to each tube is restricted to smaller sections of the visible spectrum, and the gain of each of the three channels is independently adjustable, the shortcomings of the Plumbicon colour response can to some extent be compensated. There is no doubt, however, that the red-sensitive tube will be significantly superior if consistent production of this tube, with acceptable lag characteristics, becomes possible.

5. ACKNOWLEDGEMENTS

The measurements of Plumbicon camera tube performance described in this report were carried out by Dr. C.J. Dalton. It is also desired to acknowledge the assistance given by Mr. W.D. Hatcher (Television Operations and Maintenance) and Messrs. J.L. Castle and J. Wacey (Planning and Installation Department).

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